10 Nitrogen Deficiency of Second Generation Radiata Pine in New Zealand

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EARLY IN 1962 the Nelson Conservancy of the New Zealand Forest Service drew the attention of the Forest Research Institute to the slow growth and chlorotic appearance of young Monterey or radiata pine (*Pinus radiata,* D. Don) on some tracts. These stands, 2 to 15 years old, have resulted from natural regeneration following clear felling of the original plantings at ages of 30 to 35 years. Elsewhere in New Zealand such regeneration appears to grow at least as vigorously as the parent plantations and estimates of future yields have been premised accordingly.

Though reduced growth of second generation conifers has frequently been claimed in European forestry literature, the long time spans separating generations there make rigorous comparisons difficult. In the present instance, investigation points to nitrogen deficiency as the cause of retarded growth. The occurrence of such deficiency in young, second generation stands after apparently normal growth of the original plantations is the subject of this preliminary report.

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Environmental Features

The areas in the Nelson Conservancy on which retarded stands occur are all on a formation locally termed the "Moutere Gravels," which occupies a band of some 315,000 acres through central Waimea County, South Island. The following account is largely drawn from a report by the Technical Committee on Land Utilization of the Nelson Catchment Board (*1*).

The formation represents a vast deposit, now considered Pleistocene, of gravels, sand, and silt in a graben. Though this fill is now well dissected, the ridge crests preserve a smooth surface, with a slope of approximately 1 percent for a distance of some 40 miles southwestward from Tasman Bay. The gravels are made up of greywacke, silicious slates, clay slates, grey sandstones, quartzites, and slatey breccias, now deeply weathered, particularly in the northerly, seaward portion of the formation.

The soils of the northerly portion, where the largest affected areas occur, have been classified somewhat broadly as Mapua clay loam (now sandy loam), a strongly leached moderately gammate Yellow Brown Earth in Taylor's classification (*11*). A typical profile is described as:

0–2–3 inches	Grey, friable, structureless sandy loam.
2–4 inches	Pale grey, friable, fine sandy loam.
4–24 inches	Bright yellow brown, very hard, cloddy clay vertically cracked into massive columns with some rounding of exposed surfaces and much humus staining on aggregate surfaces.
24– inches	Weathered gravels in clay matrix.

The reaction is very strongly acid throughout. Gleying occurs frequently on account of the dense substrata, and many lower slopes and depressions show a characteristic grey-white gley horizon just below the topsoil. The surface soil is noted to be particularly subject to sheet erosion, and a marked shift from upper slopes to the gullies has occurred.

Cawthron Institute workers have characterized representative profiles of Mapua clay loam at three locations, which appear applicable to the principal study area. These are given in Table 1.

The principal study area lies between Upper Moutere, Tasman, and Braeburn. The nearest source of long term climatic data is the city of Nelson, 10 to 15 miles east.[1] Average temperatures there for the two warmest months, January and February, and the coolest, July,

[1] Climatic records from the New Zealand Meteorological Service.

Table 1. Analyses of Representatives Profiles of Mapua Sandy Loam at Three Locations. From the Cawthron Institute*

Profile depth	pH	Total N	Total C	C/N	Cation exchange capacity	Exchangeable cations Ca	Mg	K	Base sat.	1% citric acid soluble P
Inches		*Percent*	*Percent*		*mc./100 g.*	*mc./100 g.*			*Percent*	*mc. percent*
Appleby										
0–9	4.7	.09			9				22	
9–21	4.6	.04			19				12	
21–33	5.1	.04			23				10	
33–40	4.9	.02			25				10	
40–48†	5.3	.02			21				17	
Cut Hill										
0–3	4.9	.18			10				27	
3–6	4.9	.08			8				23	
8–16	5.0	.05			16				10	
16–24	4.9	.04			22				6	
24–34	5.0	.03			18				3	
35–43†	5.0	.02			15				4	
Gardener's Valley										
0–3	5.0	.09	2.0	22	8.6	0.9	0.5	.14	16	1.3
3–6	5.1	.07	1.5	21	7.8	0.7	0.4	.13	14	0.8
6–9	5.0	.06	1.0	17	7.5	0.6	0.3	.06	12	0.4

* Analyses for the Appleby and Cut Hill locations are given by Riggs, Hodson, and Kidd (*In 1*); those for Gardener's Valley are from E. Chittenden, personal communication. This soil was earlier classified as Mapau clay loam on the basis of subsoil texture.

† These horizons within the underlying gravel.

are 17.1° and 7.4° C. respectively, with an annual mean of 12.5° C. Mean annual precipitation is 960 mm., uniformly distributed throughout the year. Short-term records at Motueka-Riwaka, 7 to 10 miles north of the principal area, indicate similar temperatures and somewhat higher annual precipitation, averaging 1,400 mm. over a 4-year period.

European settlement began in the mid-19th century and early survey records from the seaward end of the Mouteres indicate a sparse vegetation of *Leptospermum, Pteridium* and grasses, with patches of *Nothofagus* forest in the gullies, in contrast to more continuous forest on the same formation inland. This distribution almost certainly was caused by fires started by the indigenous Maori population, but the surveyors also commented on the poor, thin soil and stunted vegetation. Agricultural development in this area was slow or unsuccessful because of low soil fertility. From 1911 to 1916, however, an orchard "boom" led to planting upwards of 7,000 acres of apples and pears in this vicinity. These plantings largely failed, and large areas of orchard sites together with adjacent holdings were planted with radiata pine, forming the forests discussed in the present paper. Studies by the Cawthron Institute have since established the fertility requirements of these soils, enabling a productive orchard industry in the vicinity, and facilitating the present study.

Growth of Original Plantations

Growth and yield of the first-generation pine plantations within the principal study area have been generally satisfactory, although differences associated with topography were noted early. Records kept by Dr. Jamieson[2] for his plantings at Braeburn state that the plantation grew vigorously for the first eight years but thereafter a falling off in vigor and yellow foliage were apparent on one ridge. Verey and Biggs (*In 1*) in 1952, summarizing the growth of radiata on the Moutere gravels, noted that yields varied considerably, being poor on the ridges, good on the hillsides, and very good on sheltered lower slopes. The best sites on the Mouteres were said to be a little better than Rotorua Quality Class I, 111-130 feet at 25 years, with the average equal or better than Class II, 91-110 feet. Stands of Class III, less than 90 feet, were not extensive; they occurred only on the hardest sites, such as ridges where the trees often showed poor growth.

[2] L. J. Slow, N. Z. F. S., personal communication.

Further information on growth is provided by 12 randomly located plots of the New Zealand Forest Service (N. Z. F. S.) Exotic Forest Survey[3] on lands of Tasman Forests, Ltd., within the principal study area. Net mean annual increment (m.a.i.) in fully stocked 33- to 35-year-old radiata plantations ranges from 272 to 406 cubic feet per acre per year; these values ignore appreciable losses through mortality in unthinned stands. Ten of the 12 plots contain from 10,500 to 12,900 cubic feet per acre, a range in net annual growth of but 300 to 380 cubic feet per acre. Such values are consistent with Verey and Biggs' description of Quality Class II as the "average" condition.

Our observations on the Tasman Forests and elsewhere confirm that considerable erosion has occurred, much of it probably during the brief period of orchard cultivation. Narrow, convex minor ridges often have thin, discontinuous, or no A horizon remaining, whereas evidence of accumulation is found on lower slopes. The trees on these ridges may show sparse yellow-green foliage and retarded height and diameter growth. Though such extremes are of limited occurrence, they suggest that past land history may have influenced forest development over much of the area.

Growth of Natural Regeneration

As elsewhere in New Zealand, clear-felled plantations are not burned after logging. Skidding is usually by cable hauling of tree lengths over the slash. This leaves the tops, together with unmerchantable logs and dead wood, irregularly distributed. Quantities of seed are released from the serotinous cones as the slash dries, and seedlings germinate through much of the following year. Regeneration is normally well established in a year or less and reaches breast height by the third year. Excepting on eroded or gorse-covered areas, seedling numbers are often high, though their distribution is usually irregular in detail. Counts in one area of two-year-old regeneration, for example, averaged 23,000 seedlings per acre taller than 9 inches.

Hence diameter growth of the dense regeneration cannot be compared with that of the regularly spaced parent plantation, as revealed by the stumps. Nevertheless, the wide center rings of these stumps, which are recognizable up to five years after felling, provide abundant opportunity to compare the generally rapid early growth of the original stands with the varied growth of regeneration, from excellent to

[3] From T. N. Wardrop, Forest Research Institute, N. Z. F. S.; unpublished preliminary data.

poor, on the same sites. No obvious correlations between growth of first and second generations have been noted, apart from the gross topographic associations already mentioned. Such evidence, coupled with the large and persistent contrasts in height, basal area, and foliage color of seedling and sapling stands within short distances in the same felling area, clearly suggests that marked reductions in productivity have occurred since the first-generation stand developed. Visibly affected areas vary from a fraction of an acre to several acres in size, and in the aggregate amount to at least several hundred acres at present.

Table 2. RANGE IN GROWTH OF RADIATA PINE REGENERATION IN THE PRINCIPAL STUDY AREA

Area and plot number*	Age	Average DBH	Heights of dominants	Basal area	Volume
	Years	*Inches*	*Feet*	*Sq. ft./A*	*Cu. ft./A*
Valetta, #38	9	4.5	39	90	1,504
Tasman, C-3	8	....	42	....	....
Tasman, #301	7	3.7	33	49	728
Tasman, #302	8	4.1	33	46	680
Tasman, B	6–7	2.5	....	23	....
Fell and Harley, #36....	9	2.4	34	54	879

* Plots 38, 301, 302, and 36 are from the N. Z. F. S. Exotic Forest Survey; the data represent only trees larger than 1.5 inches dbh. Plot B represents only trees larger than 1.7 inches dbh, and immediately following a thinning that removed an estimated 20 percent of the basal area. The numbers of stems per acre above the stated diameter limits range from 510 to 820, except for #36 which is 1,760.

Such contrasts in growth are illustrated in Table 2, comprising data from four randomly located plots of the National Exotic Forest Survey, together with incomplete data available for an additional "good" and "poor" plot of similar age. The two-fold difference in volume production in these young stands is wider than that observed in most first-generation stands of the same vicinity. Moreover, to attain an m.a.i. of 300 to 380 cubic feet at age 35, already indicated as characteristic of first-generation stands, the young stands of Table 2 would have to approximate a m.a.i. of 150 cubic feet.[4] This is clearly not the case for the four poorer stands.

[4] From G. Duff, Forest Research Institute, N. Z. F. S., unpublished.

Methods

Procedures of analyzing foliage samples are those previously employed by Will (*16*). Foliage samples are mature current-season needles from well lighted portions of the crown. Nevertheless, differences in sampling dates and position on the tree reduce comparability among the several sets of data, although each is comparable within itself. All values for nitrogen in plant tissue and soil are based on oven-dry weight. Color notations, where given, are according to the Munsell system. The small fertilizer trials cited are simple randomized block or factorial designs, using broadcast application of commercial fertilizer carriers. Additional observations were obtained from single treated plots or series installed by the New Zealand Forest Service or H. Baigent & Sons, Ltd. Details of fertilizer applications and soil-nitrogen studies are given in sections presenting the results.

Evidence of Nitrogen Deficiency

Three types of evidence have accumulated:

1. Foliage samples were collected from paired plots, each pair representing adjacent conditions of "better" and "poorer" growth within a single age class. Distances between the members of each pair varied from 35 to 100 feet. The results, reported in Table 3, indicate a consistent association of higher foliar nitrogen with foliage color and relative growth. Though the lowest values of phosphorus and magnesium are marginal for adequate growth of this species (*18, 19*), the contents of these elements are not related to the major differences observed.

2. Nitrogen fertilizers have been applied as diagnostic trials in various combinations of location, age class, and carrier (including ammonium sulfate, urea, and nitrophoska) by foresters of the Nelson Conservancy, H. Baigent and Sons, and ourselves. In each of some 12 trials observed by or reported to us, with one exception, such applications have produced prompt and obvious increases in needle color and length of new needles. In the instances sampled, foliar nitrogen was higher as well. The results obtained at five such instances are given in Table 4. The exception noted, in which no visible response occurred, involved application of 70 pounds of nitrogen per acre as ammonium sulfate in combination with various other elements to 8-year-old regeneration. This treatment was made some months after a heavy slasher thinning that reduced a stand of several thousand saplings to 800 to 900 per acre. All trees, regardless of treatment,

Table 3. Appearance and Foliar Analyses of Trees on Paired Plots

Plot number	Age of regeneration	Appearance	Foliar content N	P	K	Mg
			Percent of oven-dry weight			
A-1	1	Yellow green	1.44	.11	.86	.08
A-2	1	Dark green	1.89	.16	1.18	.08
B-1	6–7	Yellow green; thin crown; slow growth	1.09	....	.51	.11
B-3	6–7	Dark green; vigorous; normal growth	1.73	.11	.86	.12
C-1	8	Yellow green; dominant height 34 feet	1.08	.08	.58	.13
C-2	8	Light green; dominant height 37.5 feet	1.28	.12	.76	.10
C-3	8	Green; coarse foliage; dominant height 42 feet	1.36	.12	.63	.16
D-1*	9	Yellow green; thin crowns; slow growth	1.15	.10	.57	.16
D-2	9	Green; better growth	1.34	.09	.52	.19

* This plot had received 10 cwt. per acre of reverted superphosphate 18 months prior to sampling; D-2 was untreated.

Table 4. Influence of Nitrogen Fertilization on Properties of First Year Foliage

Location	Age	Treatment* and sample position	Foliage Nitrogen content	Color	Length
	Years		*Percent*		*cm.*
Treatment I		(Lower 1/3 crown)			
Tasman	6-7	0	.87	2.5-5GY 6/8 tips 5Y 6/10	6.5-9
		100 Mg	.91	5GY 6/6-8	6.5-9
		210 N	1.22	7.5GY 4/4-5/6	12.5-14
		100 Mg + 210 N	1.15	7.5GY 4/4-5/6	12.5-14

Kainui	9	0	1.20	
		100 Mg	1.25	
		210 N	1.50	
		100 Mg + 210 N	1.35	
Williams Road	9	0	.95	
		100 Mg	.98	
		210 N	1.19	
		100 Mg + 210 N	1.19	
Treatment II				
Williams Road	9	0, Dominants—		
		upper 1/3 crown	1.49	Green
		Intermediates—		
		lower 1/3 crown	1.04	Yellow Green
		224 N, Dominants—		
		upper 1/3 crown	1.87	Dark Green
		Intermediates—		
		lower 1/3 crown	1.51	Green
Williams Road	9	0, Dominants—		
		upper 1/3 crown	1.35	
		134 to 179 N, Dominants—		
		upper 1/3 crown	1.98	

* Treatments:
I. 100 lbs./A Mg as $MgSO_4$; 210 lbs./A N as $(NH_4)_2SO_4$. Applied May 1962; sampled and measured May 1962. Same plots as Table 5.
II. Paired plots, control *vs* 224 lbs./A N as $(NH_4)_2SO_4$; control *vs* 134 to 179 lbs. as "nitrophoska" of unknown composition. Applied December 5, 1961; sampled April 12, 1962.

showed increased needle length after thinning, and it appears from other evidence that thinning increased the nitrogen status of the remaining trees, obscuring any visible effect of the moderate application.

In contrast to the prompt responses following nitrogen application, no visible effects of phosphorus, boron, or of potassium, zinc, or molybdenum alone or in combination with phosphorus and sulfur as superphosphate, have appeared thus far in trials conducted by H. Baigent and Sons at the Williams Road location of Tables 3, 4, and 5. Hence these elements do not appear to be primary limitations either to growth or to mineralization of soil nitrogen. Boron deficiency of pine has been found in part of the study area but is accompanied by characteristic symptoms which were absent from all stands discussed here. Magnesium fertilization alleviated symptoms of magnesium deficiency (*9, 18*), but such symptoms are restricted in occurrence and are largely distinct from the generalized foliage discoloration associated with nitrogen deficiency.

3. The short-term effect of added nitrogen on increment has been measured in one diagnostic trial thus far. This consists of a simple factorial application of single nitrogen and magnesium levels broadcast on unreplicated 1/40-acre plots in 6- to 9-year-old regeneration at three locations. Levels of application were 1,000 pounds per acre for both carriers, $(NH_4)_2SO_4$ and $MgSO_4 \cdot 7\ H_2O$, corresponding to 210 pounds nitrogen per acre or 100 pounds Mg per acre. The two 9-year-old stands had been slasher thinned two to three years previously, leaving approximately 900 dominant stems per acre, together with coppice shoots. The 6- to 7-year-old stand (Tasman B, Table 2) was thinned two months after treatment leaving approximately 1,600 stems per acre, one inch dbh and larger. Application was made in May 1962 and the trees measured a year later. Changes in foliage content and color on the same plots are indicated in Table 4.

Table 5 demonstrates the prompt increase in basal area increment in the first year following nitrogen application; the average increase over the controls exceeds 7 square feet per acre. An analysis of covariance to take into account differences in initial basal area shows the nitrogen response significant at the 1 percent level whereas magnesium effects are nonsignificant. Lack of separation probably reduces the full contrast between treatments in these small plots.

In addition, similar responses have been obtained by H. Baigent and Sons from four unreplicated plots in 8- to 10-year regeneration at the Williams Road location. Though the magnitude and persistence of response cannot, of course, be known from such first-year results, the increases confirm the other evidence and suggest the extent to which nitrogen deficiency retards growth.

Nitrogen Deficiency Symptoms

Symptoms of nitrogen deficiency observed in cultures (*4, 19*) are applicable in a general way to natural seedlings of comparable size. As with other nutrient disturbances of pine, however, the symptoms encountered in the field are influenced by a variety of factors, including, presumably, how seasonal variations in supply coincide with growth rate, distribution of nitrogen within the enlarging plants, and relative abundance of other nutrients. A single season's growth amounting to 20 to 40 percent of the initial basal area, for example, as observed in the control plots of Table 5, must cause marked redistribution of nutrients within the tree when external supplies are restricted. Similarly, small-scale soil heterogeneity and root competition must affect nitrogen uptake by irregularly spaced seedlings.

The latter is exemplified by observations in the previously mentioned regeneration area containing 23,000 seedlings per acre. At the end of the second year variations in the winter color of individual seedlings on control plots (numbers 12 and 5, Table 6) were noted. In the next year these variations were obscured by the flush of yellow-green new growth and by the contrast between controls and nitrogen-treated plots. At the end of the third season, however, large variations were again observed in both control and nitrogen-fertilized plots. Three color classes were recognized and characterized by sampling foliage from the upper few inches of the leaders. The composite values of 15 to 20 seedlings from each class are:

Class description	Munsell color of upper needles	Foliar nitrogen
1. All foliage dark green	10 GY 3/4	2.18%
2. Uppermost foliage dark green, remainder yellowish green	5 GY 5/6 to 7.5 GY 4/6	1.52%
3. All foliage yellowish green	2.5 GY 6/8-7/8	1.25%

A range of foliage color associated with foliar nitrogen content of older regeneration has been indicated earlier in Tables 3 and 4.

The needles of lower branches in deficient stands and on smaller trees or coppice shoots are notably more yellow green than foliage from the upper crowns of dominants; further, wherever comparable samples have been taken, they are lower in nitrogen (Table 4, II). In very deficient stands, the second-year and older first-year needles of the lower crown levels show marked apical chlorosis, sometimes followed by a tawny or tan necrosis. On individual branches this is

Table 5. Effect of Nitrogen and Magnesium on Basal Area Increase in First Year After Application

Location	Age at treatment	Basal area increase per 1/40-acre plot*†							
		Control		Mg		N		N + Mg	
	Years	*Sq. ft.*	*%*	*Sq. ft.*	*%*	*Sq. ft.*	*%*	*Sq. ft.*	*%*
Tasman	6–7	.40	40	.26	37	.52	70	.56	85
Kainui	9	.37	23	.44	26	.68	39	.61	68
Williams Road	9	.35	31	.23	21	.43	42	.38	51

* These plots identical with those of Table 4, I.

† Sq. ft. x 40 = basal area increase per acre; $\frac{\text{sq. ft.}}{\%}$ x 100 x 40 = initial basal area per acre.

Table 6. Weight and Nitrogen Status of A_{11} and Three-Inch Depth of Surface Soil Below, From Paired Plots (Table 3) and Others

Plot and transect*	Sample	pH	Oven-dry weight	Total	Nitrogen†	$NH_4-N + NO_3-N$†		
						As sampled	After incubation	
			kg./m²	*Percent*	*gms./m²*	*ppm.*	*ppm.*	*gms./m²*
Tasman—one year								
A-1	A_{11}	4.3	5.0	.19	9	8.9	58.3	.32
	A	4.6	118	.13	153	5.7	11.0	1.29
	Total				162			1.61
A-2	A_{11}	4.5	10 (est.)	.26	(26)	8.5	83.1	(.75)
	A	4.3	115	.11	126	3.6	11.7	1.34
	Total				152			2.09

Tasman—two years								
12-1	A_{11}	4.4	11.5	.36	41	8.6	655	7.53
	A	4.4	100	.25	251	6.7	20.2	2.03
	TOTAL				292			9.56
12-2	A_{11}	4.3	7.8	.38	30	16.5	111	.86
	A	4.3	103	.15	155	4.7	8.9	.92
	TOTAL				185			1.78
5-1	A_{11}	4.7	6.5	.18	12	11.2	6.3	.04
	A	4.7	93	.13	120	5.2	11.6	1.17
	TOTAL				132			1.21
5-2	A_{11}	4.5	9.0	.24	22	14.0	21.9	.20
	A	4.7	94	.15	141	5.4	16.6	1.56
	TOTAL				162			1.75
Tasman—six-seven years								
B-1	A_{11}	4.3	7.8	.22	17	8.8	57.5	.45
	A	4.3	93	.17	158	6.9	8.0	.75
	TOTAL				176			1.19
B-2	A_{11}	4.3	9.9	.22	22	8.7	27.8	.27
	A	....	98	.13	127	3.6	20.4	1.99
	TOTAL				149			2.27
B-3	A_{11}	4.2	13.6	.26	35	19.9	644	8.75
	A	4.4	111	.15	167	9.4	19.8	2.21
	TOTAL				202			10.96
Tasman—eight years								
C-1	TOTAL	4.5	95	.07	66	7.2	8.1	.77
C-2	TOTAL	4.3	94	.09	85	7.3	6.5	.61
C-3	TOTAL	4.3	92	.17	157	11.6	18.6	1.72
Williams—nine years								
D-1	TOTAL	....	96	.15	162	8.4	7.3	.79
D-2	TOTAL	....	96	.08	75	8.0	10.2	.94

* Plot designations agree with those of foliage samples from same sites in Table 3.
† gms/m² x 8.92 = lbs./A.

often progressive in appearance, affecting much of the length of proximal needles and diminishing outwards with some regularity. This discoloration is quite distinct from the high chroma apical yellowing of first-year needles that characterizes magnesium deficiency. Even without such regularity in discoloration, foliage loss is premature. The lower branches of deficient trees retain needles for only two or three years rather than up to five.

Chlorosis and early loss of needles presumably retard lower branch development. Even trees lacking obvious discoloration have narrow crowns and fine branch structure. Narrow crowns and fine branching are also associated with low levels of foliar nitrogen in this species at Woodhill Forest, which has been established on sand dunes. All appearances suggest that nitrogen content of the upper crown is maintained at the expense of crown spread, foliage density, and nitrogen content of the lower needles. This is somewhat comparable to White's findings (*15*) with potassium deficiency in *Pinus resinosa* Ait. and *Pinus strobus* L.

Perhaps as a consequence, the analyses above and in Tables 3 and 4 fail to indicate an absolute correspondence between foliar nitrogen content and degree of deficiency that would be applicable to the entire pool of data. Though the several collections were confined to mature first-year foliage, they vary in time and position on the tree. In contrast to the present observations, previous investigations (*16*) in Kaingaroa Forest, where nitrogen deficiency is unknown, revealed no such variation of nitrogen content with decreasing height within the crown. Absolute correspondence is further complicated by observations such as those of Tamm (*10*) who reported large year-to-year variations within the same stands of *Pinus sylvestris* L. The ranges observed in eight annual collections were from 1.29 to 1.68 percent N on a control plot, and 1.62 to 2.23 on a nitrogen-fertilized plot. Though general ranges of deficiency and adequacy are evident from Tables 3 and 4, much closer correlations are desirable, and probably obtainable when the sources of variation are better known.

Nitrogen Availability

Several of the known or presumed sources of nitrogen addition appear inoperative in the acid, infertile upland soils of the northern Mouteres. Legumes are lacking, with the exception of gorse, *Ulex;* though this is now common it seems to have little effect on the nitrogen status of associated vegetation. *Coriaria* is confined to favorable sites not considered here. The arboreal lichens so conspicuous in the North Island plantations are absent in this climate. The sheltered

waters of Tasman Bay presumably give rise to little, if any, transport of nitrogen inland in the manner described by Wilson (*20*). Hence, apart from small additions in rainfall and whatever nonsymbiotic fixation may be postulated, the source of nitrogen available to the regeneration seems to be chiefly that already contained in the parent stand, in the surface organic layer, and within the mineral soil.

Orman and Will (*2*) have previously estimated the quantities of nitrogen contained in the aboveground portions of radiata plantations on the pumice soils of Kaingaroa Forest, North Island. The stand examined was similar in site quality to the Tasman first-generation stands already cited, but somewhat younger, 26 years old. Because of age and mortality from *Sirex* it was lower in volume, 6,900 cubic feet per acre as compared to 10,500 to 12,900 cubic feet for the 10 Tasman stands. The total nitrogen content of the aboveground stand was 197 pounds per acre, but 42 percent of this, 83 pounds per acre, would have remained in the slash left on the site following clear felling and close utilization of stem wood. The nitrogen contained in the foliage, 49 pounds per acre, accounted for more than half that left in the slash and, indeed, for 25 percent of the aboveground total. Though other estimates for *P. radiata* in Australia (*7*) are somewhat higher, they are based on single tree samples.

No similar data are available for first-generation stands of the Moutere area, but allowance for their greater cubic volume and for the probable content of the roots (e.g., *3*) suggests that the nitrogen contained in the 30- to 35-year-old Tasman Forests plantations can scarcely exceed 300 to 400 pounds per acre. This is a measure of the amount supplied by the soil to the original plantations of radiata on sites where nitrogen deficiency now prevails. Taking into account both root systems and a lower wood removal than Orman and Will assumed, it is likely that more than half the nitrogen contained in the Moutere stands remains after clear felling.

The additional quantity of nitrogen in the surface organic layer at the time of felling is unknown but cannot be large. This layer averages less than one inch thick over most of the areas, an H layer is essentially lacking, and the L and F layers consist of loose, coarse pine needles, twigs, and cones. From related information (*17*) it appears unlikely that the surface layer contains more than 100 pounds nitrogen per acre.

Most of the surface is little disturbed by felling, although a small percentage is swept clean in skidding, and some soil movement and incorporation of debris results. The heavy slash is irregularly distributed, but wholly slash-free areas larger than 1/80 of an acre are few. Breakdown of the litter, foliage, and fine twigs is rapid, and

these are largely unrecognizable at the end of the second year after felling. Reduction of branch and stem wood is much slower, particularly since part of it is held above the soil surface during the first few years. Only scattered decaying logs and especially, groups of logs are recognizable after six to eight years, however.

Observation of logged areas in their first year indicates a moderate flush of nutrient release, shown by the dark green color of pine seedlings and the color and height of annual weeds such as thistle and wild lettuce. This is most marked near concentrations of needle-bearing slash, whereas plants on areas swept free of slash and litter may be yellow-green. Such a contrast is represented by samples A-2 and 1, respectively, in Tables 3 and 6. Visible evidence of accelerated release is entirely lacking in subsequent years, however, and extension of a grass and shrub cover proceeds slowly.

Hence, it appears, as might be expected, that some part of the nitrogen in the litter and slash becomes available shortly after felling, very probably in greater amounts than the irregularly distributed new vegetation can utilize. On the other hand, there is no apparent relation of seedling color and growth after the first year to the irregular concentrations of woody slash, nor is the disappearance of woody slash in 6- to 12-year-old areas accompanied by any perceptible change in appearance of the regeneration. Evidence of immobilization is apparent only in the vicinity of hauler locations, where the large quantities of wood and bark incorporated in the soil induce extreme nitrogen deficiency in young pine seedlings.

Experimental

The nitrogen status of the surface soil was examined as a reconnaissance study. Sampling took place in July (in midwinter) and was confined to a few locations in the Tasman Forests and vicinity: the paired plots of Table 2 and within the control plots of a fertility experiment in the area of two-year regeneration already described under *Nitrogen Deficiency Symptoms*. Age of the regeneration varied from 1 to 9 years. At each site, 10 or 15 fixed area samples, according to thickness, of the surface organic layer and 10 of the upper 3 inches of mineral soil were taken systematically at 2- or 3-foot intervals along a 33-foot tape line; this is equivalent to a line transect through a square 1/40-acre plot. In the 8- and 9-year-old stands, however, a separable A_{11} could no longer be clearly distinguished and a single sample was taken of the surface 3 inches. The individual point samples were composited to form transect samples representing a total area of either 533 or 800 sq. cm. of the A_{11}, or 96.5 sq. cm. (733 cu. cm.) for the mineral soil immediately below.

The composited samples were weighed moist and sent by air to the New Zealand Department of Agriculture Laboratory at Rukahia. Maximum temperatures encountered in transit were probably 15° C. or less. Nitrate and ammonia nitrogen were determined in the moist soil upon arrival and again following incubation of samples in polyethylene bags for 28 days at 25° C. Moisture content of the mineral samples during incubation was about 60 percent of field capacity; that of the organic samples, 50 to 60 percent of dry weight. Subsequent determinations were made of dry weight, reaction, and total nitrogen by the Kjeldahl method.

Table 6 presents the concentrations observed as well as the calculated amounts per unit area.

Though sampling was unreplicated within the paired plots, comparison of the four values from Plots 12 and 5 illustrate variability within a two-year-old regeneration area. These two plots, about 300 feet apart, are the randomly located controls of a fertilizer experiment in a seemingly homogeneous and deficient seedling stand; each is represented by two randomly located transects across an interior 1/40-acre sub-plot. Transect 12-1 is markedly higher in total and mineralizable nitrogen than the other three, which deviate little from average values of Table 6. The transects are short and the actual area sampled is exceedingly small, however, in comparison with the dimensions of many natural irregularities and those induced by logging. The range in amounts released upon incubation is of particular interest in view of the large variation in color and nitrogen status of individual seedlings on this area during the season after sampling, as described under *Nitrogen Deficiency Symptoms.*

The samples from Plots B-1 and B-2 are likewise replicates, in effect, representing central transects for adjacent 1/40-acre plots in a deficient 6- to 7-year-old stand (described in Tables 3, 4, and 5). Values for these two do not differ appreciably from the lower three mentioned above. An analysis of variance extending over the six plots shows no significant differences associated with location for any of the three categories of nitrogen.

The thin A_{11} horizon, which includes any traces of A_0, contains a relatively small amount of total nitrogen, ranging from 75 to 370 pounds per acre. This concurs with earlier-mentioned observations of the light A_0 horizon of the parent stand and its rapid disappearance. Despite its higher percentage content, the A_{11} contains only about 10 to 20 percent of the 1,200 to 1,800 pounds of total nitrogen in the combined layers. Within this limited sample there is no indication that either weight or content of the A_{11} diminishes with time

beyond the first year after felling, although the distinction of this layer becomes less marked.

The percentage content in the 3-inch depth samples varies, for the most part between 0.11 and 0.17 percent, in substantial agreement with Table 1. The lower values of C-1 and C-2 result from surface erosion, whereas the sampled layer of D-2 appears to be a deposit of eroded material from the slope above.

The concentrations of ammonia and nitrate nitrogen at the time of sampling are small; presumably they are influenced by mid-winter temperatures and by rains that left the surface soil at field capacity or above. The concentration of ammonia-nitrogen increases markedly in the A_{11} samples upon incubation, but the amounts are related to neither the weight of the layer nor its total nitrogen percentage. Increases in nitrate-nitrogen amount to less than 5 ppm.

With but two exceptions, the amounts of nitrogen mineralized during incubation are small when converted to an area basis, the totals after incubation amounting to but 5 to 20 pounds per acre. In the two exceptional samples, 12-1 and B-3, more than three-fourths of the very much higher totals, 85 and 98 pounds per acre, is attributable to mineralization of the A_{11}. Variability within Plot 12 has been commented on above. In the case of B-3, however, a probable contribution of the present stand to the readily mineralizable nitrogen of the A_{11}, must be acknowledged. Nitrogen status of the current foliage is high, 1.73 percent, and Will (*17*) has found vigorous regeneration of this age at Kaingaroa to have a litter fall of about 3,500 to 4,500 pounds per acre per year.

The population represented by Table 6 is too small and diverse to reveal any but simple and well marked correlations. Moreover, though sampling was confined to the upper layers where the greatest concentrations of nitrogen and most rapid transformations occur, estimates from Table 1 suggest that these layers contain no more than one-third of the total present, at least in uneroded profiles. In any case, no relationship is evident between total nitrogen content or quantity mineralized during incubation on the one hand, and foliar nitrogen or relative growth described as "better" or "poorer" (Table 2), on the other.

Nitrogen Uptake

The probable quantity of nitrogen contained in 30- to 35-year-old first-generation stands has been discussed above. Other studies by Will[5] at Whakarewarewa Forest, North Island, demonstrates that at

[5] G. M. Will; to be published.

the age of 12 years natural second-generation stands of Quality Class I already contain most of the nitrogen needed to sustain them for another two or three decades under management. The nitrogen released by thinning approximately equals the subsequent requirements of the stand to age 35. The 12-year-old stand studied had accumulated approximately 150,000 pounds of dry matter per acre in aboveground tissue. This contained 335 pounds nitrogen per acre distributed as follows:

Live foliage and twigs	135 pounds per acre
Live branches and stems	145 pounds per acre
Dead branches; stems and litter in branches	55 pounds per acre

To arrive at the total amount of nitrogen withdrawn from the soil, the amounts in roots and undecomposed forest floor must be added. Hence, discounting the first year, the average net withdrawal would have been some 40 to 50 pounds nitrogen per acre per year over an 11-year period, apart from retention in a developing litter layer. Total annual uptake would include the quantity cycled in the litter; this is initially zero, of course, but approaches 40 pounds per acre annually by the seventh or eighth year at this forest (*17*).

Application of such values to the Moutere problem involves the obvious distinction between the quantity of nitrogen contained in a stand and that actually required for its growth, as well as the somewhat lower growth rates prevailing there. Annual requirements implied are nevertheless large when compared with the small total contents of the A_{11} horizons and the slow mineralization in the upper mineral soil during incubation (Table 6).

Discussion

Although the evidence at hand is incomplete, it appears to establish three points:

1. Mapua sandy loam, the broadly defined soil series on which most, but not all of the affected stands occur, is a relatively deeply weathered soil. By New Zealand criteria (*12*) it is very strongly to extremely acid, low in total nitrogen and base saturation, and marked by lack of structure in the surface horizon. Land clearing, cultivation, and erosion prior to establishment of radiata pine plantations appear to have reduced its already low available nutrient supplies and increased the subsequent importance of small order variations. Satisfactory crop and orchard growth is now maintained on these soils

through application of fertilizers and soil amendments, indicating that physical properties, *per se,* are not primary limiting factors.

2. Despite fertility limitations, the first crop of pine has grown satisfactorily over most of the area after overcoming any initial limitations. Well stocked, unmanaged stands have produced in the vicinity of 10,000 to 13,000 cubic feet per acre in 30 to 35 years. To allow such growth, the net removal of nitrogen from the soil must have been between 200 and 300 pounds per acre as a minimum; a large part of this may have bee decade of growth. Additional immobilization in the thin surface humus layer has been small and this, together with at least half of the amount contained in the living stand, remains after clear felling and removal of logs.

3. Dense natural regeneration of radiata pine is well established within some months after clear felling. In the first year, competition is usually slight and the total mass of green plant tissue small. Seedling development is normal, and plant appearance and composition suggest that the available nitrogen supply is adequate over much of the area. Beginning in the second year or later, however, and continuing for at least 10 years (few second growth stands are older), growth of the young trees at many locations is retarded by chronic nitrogen deficiency. It is evident that the amount of nitrogen available from the soil is much lower than the cumulative requirements for normal foliage density and content and immobilization in other tissue and litter. These needs could be met by a net uptake of less than 50 pounds per acre per year during the first decade of growth.

There is no convincing explanation of the inferred difference in nitrogen availability to the first and second generations of pine, some 35 years apart in origin, on the same sites. Most of the numerous hypotheses that might be considered elsewhere seem inapplicable. There is no question here of immobilization in raw humus, (e.g., *21*), removal of thinnings or litter, or loss through ground fires, slash burning, soil disturbance, or prolonged soil exposure. The observations of Stevens and Bond (*7*) on the poorer growth of second-generation radiata pine in Australia seem to parallel ours but differ in that the logging slash from the first crop was burned. The latter is also true of the experimental areas from which Waring (*14*) reported nitrogen and phosphorus responses in second-generation plantings.

Depletion of nitrogen through removal of wood and bark is real, although its magnitude, probably less than 150 pounds per acre (*2*), is not great when compared with the total amount in the profile and the opportunity for transformation in the course of a third of a

century. Such depletion is probably augmented, however, by some loss of the most readily soluble fraction from slash and litter during the first season after felling. Rennie (*5*), among others, has recently emphasized the significance of removal of nutrient elements from soils low in natural fertility.

In addition to actual losses, immobilization of nitrogen during decomposition of the logging slash and root systems is an inviting hypothesis. The large mass and wide C/N ratio of such material offer obvious arguments for such immobilization. Contradicting observations, however, are the lack of any negative association between localized accumulations of slash and seedling growth, and the persistence of nitrogen deficiency for at least 12 years, well past the time when visible residues have disappeared from most of the soil surface. Nor does the limited evidence of the incubation trial suggest that immobilization is greater in the younger regeneration areas.

Additional hypotheses are suggested by two other studies of nitrogen transformation under pine. Van Goor (*13*) has attributed decreased growth of second, or second and third generation Scots pine on sandy soils in Holland to deep (i.e., 50 cm.) tillage immediately prior to the first pine crop. As contrasted with untilled soils under pine, the tilled soils appeared to have lost about 30 percent of the total organic matter and nitrogen in the profile, as well as some phosphorus, over a 50- to 100-year period. In effect, deep tillage accelerated mineralization and increased growth of the first crop, but at the expense of stable fertility levels and growth of the following stands. Though the resemblance of soil and antecedent treatment to the Moutere situation is remote, the indication of long-term changes in nitrogen availability as a result of prior treatment is relevant.

Richards (*6*) has described increased availability of nitrogen in first-generation stands of *Pinus taeda* L. and *P. elliottii* Engelm. in Australia; evidence for this is based on repeated instances of apparent nitrogen response by hoop pine, *Araucaria,* when planted under or within the lateral root extent of the pine.

Observations such as those of Richards are known to many foresters who have watched pine plantations develop on soils formerly in grass, heath, or other nonconiferous vegetation. To exemplify only with firsthand observations of the authors, in New York State, *Fraxinus americana* L. seedlings in old fields respond strongly to added nitrogen; they also exhibit similar improvement in color and growth whenever interplanted *Pinus sylvestris* begin to close canopy about them. Again, at the Golden Downs State Forest in New Zealand, *Cupressus macrocarpa* Gord. and *Chamaecyparis lawsoniana* (Murr.) Parl. in pure plantations are retarded in growth and bear

sparse, chlorotic foliage; this condition is alleviated by nitrogen fertilization.[6] Improved color and growth rate are conspicuous, however, wherever these species border on adjacent plantations of *P. radiata,* or near overtopping volunteer pine. However inexact such individual observations may be, their concurrence supports Richards' contention that ". . . *Pinus* itself, either directly or indirectly, is responsible for increasing the supply of nitrogen . . ."(*6*).

Yet, the evidence of nitrogen deficiency in second-generation stands is wholly contrary to claims of nitrogen fixation by *Pinus radiata* (*8*), or to any necessary permanency of the increased availability discussed by Richards. Waring (*14*) states a similar conclusion.

These several observations of nitrogen availability and deficiency can be reconciled by a hypothesis which simply credits the pine root complex, including its associated microflora, with a capacity to break down some fraction of the soil organic matter that had been inaccessible or resistant to the previous flora. The nitrogen released might be larger or smaller in amount, and be either wholly immobilized in the new ecosystem or recycled in part. Accelerated release presumably would be most appreciable during the initial spread of the pine root system, and would diminish thereafter with availability of the substrate; continuation of the same root microflora by later ages or generations of pine would not bring renewed increases. Such a hypothesis is not inconsistent with the several observations above, but confirmative support for it is entirely lacking.

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